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The sounds of the stars

Data from NASA's Kepler space telescope have revolutionized the search for planets outside the Solar System — and are now doing the same for asteroseismology.

BY RON COWEN

Most astronomers gaze at the heavens and see stars. William Chaplin hears an orchestra — a celestial symphony in which the smallest stars are flutes, the medium-sized ones are trombones and the giants are reverberating tubas.

The sounds are internal vibrations that reveal themselves as a subtle, rhythmic brightening and dimming of a star, explains Chaplin, an astrophysicist at the University of Birmingham, UK, and a specialist in asteroseismology. These waves provide information that astronomers can't get in any other way: triggered by the turbulent rise and fall of hot gases on the star's surface, the vibrations penetrate deep into the stellar interior and become resonating tones that reveal the star's size, composition and mass (see 'Celestial music'). So by watching for the characteristic fluctuations in brightness, says Chaplin, "we can literally build up a picture of what the inside of a star looks like".

Better still, he adds, asteroseismologists are now hauling in the data wholesale. After years of being hampered by Earth's turbulent atmosphere, which obscures the view of the Universe and has limited asteroseismology to about 20 of the brightest nearby stars, researchers have been astonished by the trove of information coming from a new generation of space observatories. Thanks to the French-led Convection, Rotation and Planetary Transits (COROT) space telescope, launched in 2006, and NASA's Kepler space telescope, launched in 2009, they can now listen in on hundreds of stars at a time.

"We are in a golden age for the study of stellar structure and evolution," says Hans Kjeldsen, an astronomer at Aarhus University in Denmark.

"Nature seems to have been kind to us," agrees Ronald Gilliland, an astronomer at Pennsylvania State University in University Park. "The stars seem not to be shy about showing us lots of oscillations that will allow us to reveal their innermost secrets." The flood of data has shed light on the interior of red-giant stars, and forced astronomers to question their understanding of how stars and galaxies form.

Stellar serendipity

Asteroseismology isn't the main mission of either COROT or Kepler: they are intended to hunt for planets outside the Solar System (exoplanets) that have roughly the size and orbital radius of Earth. But because they both look for the tiny dip in brightness caused when a planet transits, or passes in front of, its parent star, they both have to record a drop in stellar brightness of no more than 1 part in 1,000. And that, in theory, makes them able to detect the effects of the stellar sound waves.

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Before launch, no one could say whether the satellites would make good on this. Kepler's exoplanet search has, in fact, been hindered by stellar oscillations that obscure transits, but are caused by magnetic activity[1], so are unrelated to sound waves. Acoustic oscillations and transits don't interfere with each other: sound waves cause the brightness of Sun-like stars to vary on time scales of 5–15 minutes, whereas planetary transits last for hours. So the planners for both COROT and Kepler were happy to include asteroseismologists in their mission teams. "We are riding on the back of the planet hunters," says Douglas Gough, an asteroseismologist at the University of Cambridge, UK.

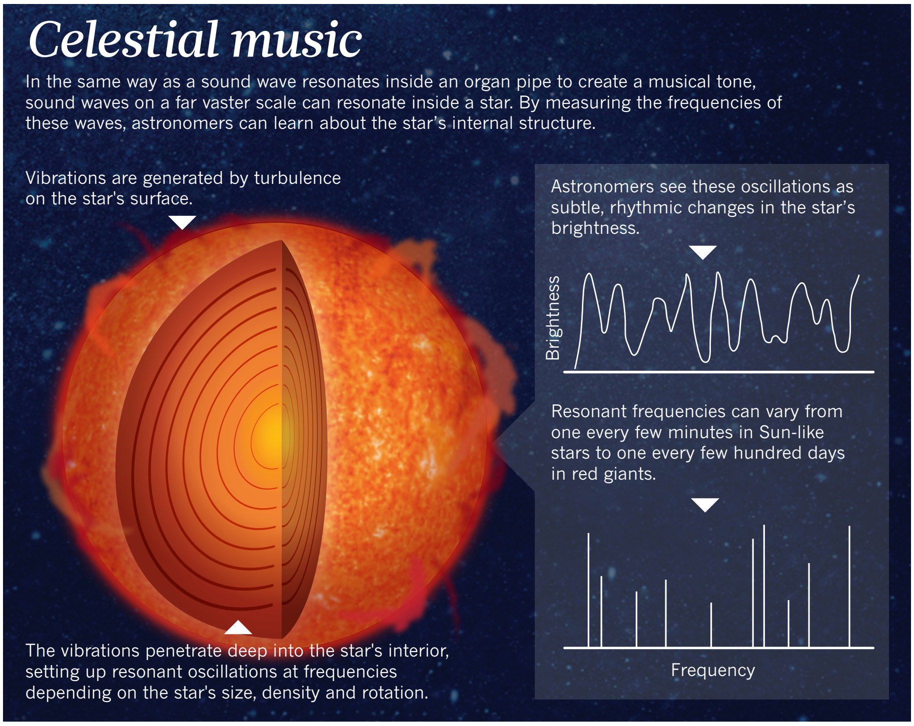
As it turned out, the sound-wave data came down in an avalanche — especially from Kepler, which has a 0.95-metre-aperture telescope — nine times the sensitivity of COROT's — plus the ability to look at a larger group of stars for a longer period of time than COROT.

"Everything came together marvellously well," says Gilliland.

Last April, Chaplin and his colleagues published their analysis[2] of acoustic oscillations observed by Kepler in 500 Sun-like stars. The frequency and amplitude of the oscillations revealed that the stars have roughly the sizes predicted by established theories of astrophysics, but the distribution of their masses turned out to be significantly lower than expected.

Chaplin isn't yet sure what to make of these findings. But if further observations of the same stars continue to show masses lower than estimated, theorists may have to rethink models of star formation and galaxy assembly. "We didn't have a way of testing these models until we began doing the asteroseismology with Kepler," says Chaplin. And getting them right is crucial: not only do stellar masses underlie theories of galaxy formation, they are also essential for understanding how thermonuclear reactions in stars have produced heavy elements throughout the history of the galaxy — heavy elements that eventually formed planets including Earth.

"This is amazing to witness," says Kjeldsen. With the latest data, he adds "we can test our assumptions, ideas, theories and models in great detail. And we can correct all our errors too."



Secrets of the giants

Some of Kepler's biggest surprises have been in its sounding out of red giants. These are Sun-like stars that have exhausted the hydrogen at their cores, causing a fuel crisis that paradoxically leads them to swell up to more than 100 times their original diameters. In about 5 billion years' time, for example, the Sun will become a red giant big enough to devour the innermost planets of the Solar System.

Astronomers would like to be able to distinguish between two phases of red-giant evolution: an early stage, in which the giant is still fuelled by hydrogen in a thin shell around a dense core only a few times bigger than Earth; and a later stage, in which the star has begun burning the helium at its core. Knowing the difference would help them to determine the red giants' ages, how quickly they evolve and the amount of gas and heavy elements that they shed into interstellar space during each phase.

That was impossible until Kepler: from the outside, a red giant looks the same regardless of what it is burning. But last March, Timothy Bedding, an astronomer at the University of Sydney in Australia, and his colleagues reported[3] that Kepler oscillation data allowed for a clear distinction.

"It's difficult not to be fascinated by an ability to learn about the properties of the tiny core of these huge stars from oscillations on their surface," says Jørgen Christensen-Dalsgaard, an astronomer at Aarhus University and a co-author of the study.

Going further, the same researchers reported in December[4] that they had measured the rotation rate of the core region of a red giant for the first time, and discovered that it whips around about ten times faster than the surface.

This finding confirms the standard model of red-giant formation — Sun-like stars flinging their shallower layers outwards while their cores contract. Basic physics demands that angular momentum is conserved, so the outer layers must slow their rotation and the contracting core must speed up, just as observed.

Mission not yet accomplished

Many astronomers have called for an extension to Kepler's mission, which is currently slated to end in November. It is unclear whether NASA will be able to heed them; funding is tight, and other missions need money, too. But asteroseismologists are helping to make the case. They point out, for example, that acoustic oscillations in the Sun shift their frequency ever so slightly — a change of about 1 part in 10,000 — over the course of the Sun's 11-year magnetic cycle. The shift provides a new way to measure the length of the cycle, in which changes in the Sun's magnetic field drive sunspots, flares and other fluctuations in energy that can wreak havoc on Earth's satellites and communication systems.

Astronomers would now like to compare the Sun's magnetic-activity cycle with those of a slew of similar stars. If the other stars have cycles extending over many years, says Gilliland, Kepler's baseline mission will not be able to track them. "But with observations extending to 7–8 years, or even more — the spacecraft seems good to allow 11 — we will be able to probe many stellar activity cycles. It would be profoundly more powerful," he adds.

An extended mission could also allow astronomers to learn more about a different class of oscillation that originates deep in a red giant's core, and could tell them a great deal about the core's structure and density. These oscillations have a very small amplitude by the time they make their presence known at the surface, but their reverberations are persistent, like those of a heavy bell, lasting for months or years. "We've just begun to wring the interesting astrophysics out of these results," says Gilliland, and the ability to take data over many years would be an immense help.

Asteroseismology may even help in Kepler's primary mission of finding Earth-sized exoplanets orbiting in the habitable zone around their stars, notes Chaplin. Because the craft can detect an exoplanet only by the amount of light that it blocks as it passes in front of its host star, and can measure it only in relation to the host, the radius of a planet is known only as accurately as the radius of the star. But sound-wave oscillations recorded from the parent star can pin down its size very accurately[5]. Such measurements are possible for only the brightest of the stars in Kepler's field of view, but they could make a huge difference in the researchers' confidence in their data as they begin to report detection of planets approaching Earth's size[6,7].

Johannes Kepler, the seventeenth-century astronomer after whom the spacecraft was named, theorized that Earth and all the other known planets made their own sounds — an arrangement that he called the music of the spheres. It would be only fitting if celestial music, of a kind, had a key role in the Kepler space telescope's most prized discovery. ■

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